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FROM: PROI (TI) (STINFO) 01 Aug 2000

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-TP-2000-158**
Wei, Y., Chow, C.L. (University of Michigan); Liu, C.T. (AFRL/PRSM), "Damage Analysis for Mixed Mode Crack Initiation"

International Conference on Computational Science **(Statement A)**
(Anaheim CA, 21-25 Aug 00) **(Submission Deadline: 16 Aug 00)**

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Damage Analysis for Mixed-Mode Crack Initiation

? hyphenated in conclusions...

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~~OBJECTIVE~~

Introduction ?

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Prediction of mixed-mode fracture load and crack initiation angle for Al 2024-T3 and particulate composite material with the theory of damage mechanics

Objectives

1) Develop a model to characterize damage in a material element.
2) Propose a failure criterion with the concept of damage accumulation
3) Implement the damage model into ABAQUA through UMAT subroutine.
4) Apply the model for mixed-mode fracture analysis.

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DAMAGE MODEL

Relationship Between Effective and True Stress

$$\overline{\sigma} = \mathbf{M(D)} : \sigma$$

The damage effect tensor **M(D)** is expressed with two damage variables D and μ as

$$\mathbf{M} = \frac{1}{1\text{-}\mathrm{D}}\begin{bmatrix} 1 & \mu & \mu & 0 & 0 & 0 \\ \mu & 1 & \mu & 0 & 0 & 0 \\ \mu & \mu & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1-\mu & 0 & 0 \\ 0 & 0 & 0 & 0 & 1-\mu & 0 \\ 0 & 0 & 0 & 0 & 0 & 1-\mu \end{bmatrix}$$

DAMAGE COUPLED CONSTITUTIVE EQUATION

The elastic law of damaged material

$$\varepsilon^e = \mathbf{C}^{-1} : \sigma \qquad \mathbf{C}^{-1} = \mathbf{M} : \mathbf{C}_0^{-1} : \mathbf{M}$$

C_0 and C are elastic tensors respectively for undamaged and damaged materials

The yield surface is postulated with damage consideration as

$$F_p(\sigma, R) = \frac{1-\mu}{1-D}\sigma_{eq} - [R_0 + R(p)] = 0$$

σ_{eq} the Von-Mises equivalent stress

The plastic law of damaged material

$$d\,\varepsilon^p = \lambda_p \frac{\partial F_p}{\partial \sigma} \qquad dp = \lambda_p \frac{\partial F_p}{\partial(-R)} = \lambda_p$$

DAMAGE SURFACE

The plastic damage surface is

$$F_d(Y,B) = Y_d - [\,B_0 + B(w)\,] = 0 \qquad Y_d = \left\{ \frac{1}{2}\left(Y_D^2 + \gamma\, Y_\mu^2 \right) \right\}^{1/2}$$

Y_D, Y_μ	the thermodynamic conjugate forces of the damage variables D and μ
B_0	the initial damage threshold
B	the damage hardening
w	the equivalent damage
γ	the damage-related material constant

DAMAGE EVOLUTION

$$dD = -\lambda_d \frac{\partial F_d}{\partial Y_D} = -\frac{\lambda_d Y_D}{2Y_d}$$

$$d\mu = -\lambda_d \frac{\partial F_d}{\partial Y_\mu} = -\frac{\lambda_d \gamma Y_\mu}{2Y_d}$$

$$dw = -\lambda_d \frac{\partial F_d}{\partial B} = \lambda_d$$

λ_d the Lagrange multiplier

FINITE ELEMENT FORMULATION

The proposed damage model is discretized and coded in the user subroutine UMAT of a finite element package ABAQUS (version 5.8).

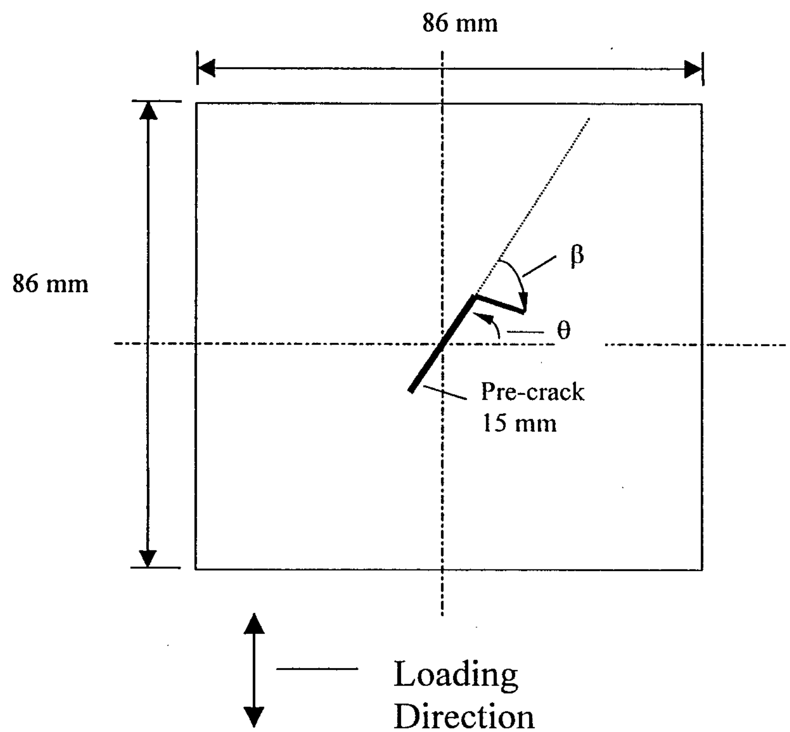
$$d\sigma = \mathbf{C}^{ep} : d\varepsilon \qquad\qquad \mathbf{C}^{ep} = \mathbf{M}^{T,-1} : \mathbf{U}^{T,-1} : \mathbf{C}_0^{ep} : \mathbf{M}^{T,-1}$$

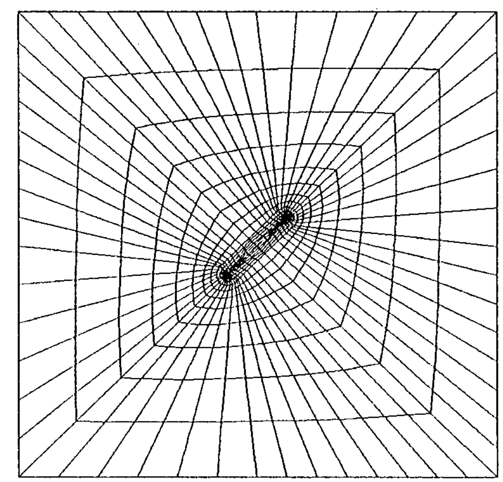
C^{ep} the effective instantaneous tangent modulus tensor

$$\mathbf{U} = \mathbf{I} - \left(\mathbf{U}_0 + \mathbf{C}_0^{ep} : \mathbf{M}^{T,-1} : \mathbf{U}_0 : \mathbf{M}^{T,-1} : \mathbf{C}^{-1}\right) : \sigma : \mathbf{T} : \mathbf{M}^{T,-1}$$

$$\mathbf{U}_0 = \frac{\partial \mathbf{M}}{\partial D}\frac{\partial F_d}{\partial Y_D} + \frac{\partial \mathbf{M}}{\partial \mu}\frac{\partial F_d}{\partial Y_\mu}$$

Crack Initiation Angles for Al 2024-T3 Plates





Typical finite elements
for mixed-mode fracture analysis
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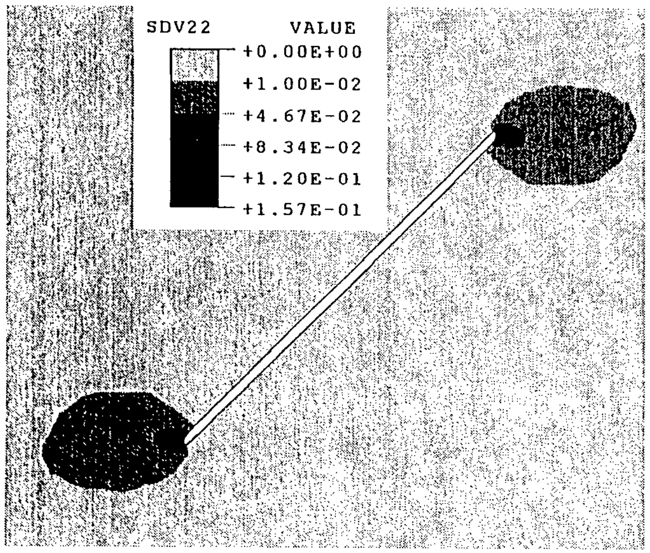
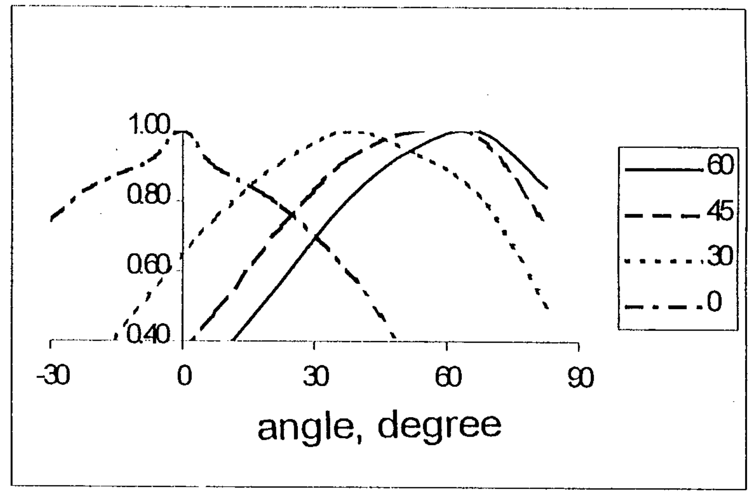
Crack Initiation Angles for Al 2024-T3 Plates



Damage distribution contours in AL2024-T3 plate for $\theta = 45^0$



Angular distributions of damage for mixed-mode AL2024-T3 specimen
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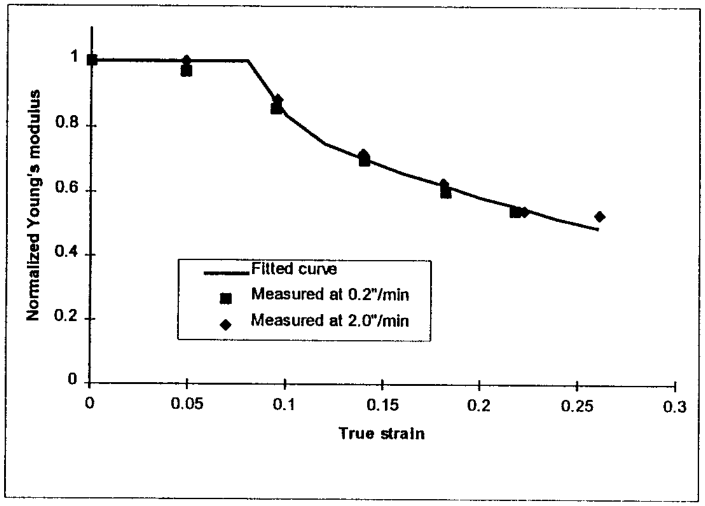
Crack Initiation Angles for Al 2024-T3 Plates

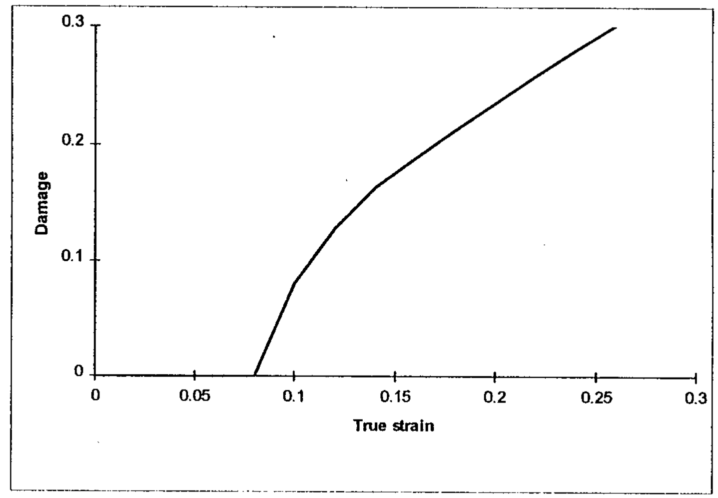
Table 1 Crack Initiation Angle β_i for Al2024-T3

inclined angle θ	test	numerical simulation	
		proposed model	Chow&Wang's model
0	0	0	0
30	35.9	37.5	43
45	53.7	52.5	56
60	71.2	67.5	73

Measurement for Particulate Composite Plates

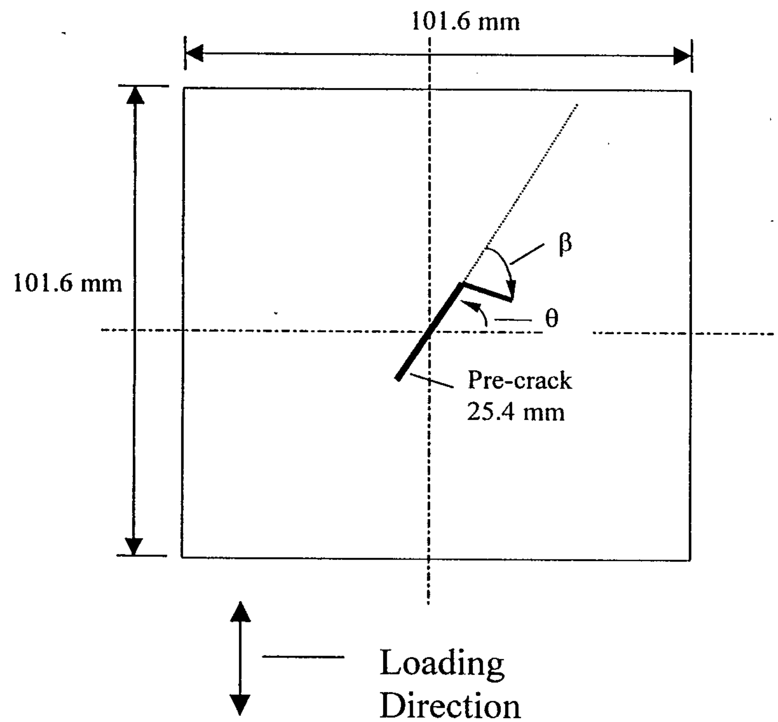


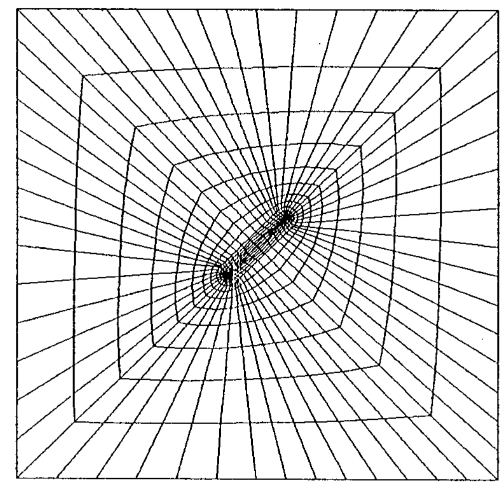
Normalized Young's modulus vs. applied strain for a particulate composite



Damage evolution curve for a particulate composite

Fracture Analysis for Particulate Composite Plates





Typical finite elements
for mixed mode fracture analysis

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Fracture Analysis for Particulate Composite Plates

Table 2 Crack Initiation Load for Particulate Composite

Pre-crack angle (^{o})		0	30	60
Load (lb)	prediction	24.0	27.2	36.9
	test	23.4	27.0	36.2

Table 3 Crack initiation Angle β_i (^{o}) Particulate Composite

Pre-crack angle θ (^{o})		0	30	60
β_i (^{o})	prediction	0	28	62
	test	0	33	68

Conclusions

(1) Numerical modeling result indicates that damage accumulation is confined around the crack tip region.

(2) For 2024-T3 Al, both the isotropic and the anisotropic damage models can be used to predict the crack initiation loads and angles under mixed-mode loadings with good accuracy.

(3) For the particulate composite material, the predicted crack initiation loads and angles, based on the proposed isotropic damage model, agree well with the test results.

(4) Both the crack initiation loads and angles increase with increasing the initial crack inclined angles.